

BODILY INTERACTIONS IN MOTION-BASED MUSIC APPLICATIONS

Marcella Mandanici

*Department of Information Engineering
University of Padova
Italy*

Antonio Rodà

*Department of Information Engineering
University of Padova
Italy*

Sergio Canazza

*Department of Information Engineering
University of Padova
Italy*

Abstract: *Motion-based music applications exploit the connection between body movements and musical concepts to allow users to practice high-level structured elements (e.g., tonal harmony) in a simple and effective way. We propose a framework for the design and the assessment of motion-based music applications by involving outcomes from various disciplines, such as the cognitive sciences and human–computer interaction. The framework has been applied to a working system, the Harmonic Walk, which is an interactive space application based on motion-tracking technologies. The application integrates both digital and physical information by reacting to a user’s movements within a designated 3 x 4 m floor, where six musical chords have been arranged according to a determined spatial positioning. Human choreographies from the user’s coordinated movements to musically structured events are analyzed in order to determine their relationships and to discuss related design issues.*

Keywords: *interactive spaces, reality-based interaction, conceptual blending, implicit knowledge, human choreographies.*



INTRODUCTION

Interactive spaces are two-dimensional surfaces or three-dimensional regions positioned within a range of sensors or a network of control devices for detecting the presence, the position, and/or the gestures of one or more users within the space. Two-dimensional surfaces may be floors, touchscreens, or interactive walls; three-dimensional regions may be positioned anywhere and may be user- or sensor-centered.¹ Both two- and three-dimensional spaces belong to everyday life and, consequently, may offer users an immediacy of interaction and effective feedbacks. Applications that employ interactive spaces as their interfaces have the power to mix the reality of the physical space with the richness and variety of a digital domain and, in doing so, to connect the real with the digital via a reality-based interaction style (Jacob et al., 2008). The user acts and moves in the physical space but, through her/his movements, s/he can reach and interact with expressly arranged digital contents, bringing to life a responsive augmented reality. Bill Buxton, while writing his reactive environments design principle 5, said that cameras and microphones used for human–human interaction could also be considered a computer’s eyes and ears, respectively (Buxton, 1997) and thus be employed as well as a means for human–computer interaction. As for cameras, some computer processes may be fed by motion and gestural data; as a consequence, the digital content needs to be arranged within the physical space to be made available to the user. This principle is the core idea of reality-based applications. It describes the birth of interactive spaces where the computer protrudes into reality through digital-content spatial organization, and where the user enters the digital content through bodily motion. As a consequence, bodily motion can be regarded as the leading factor for human–computer interaction in environments such as these.

The aim of this paper is to explore the nature and quality of motion as a means of bodily interaction in environments where music is produced or heard. Movements coordinated with musical events depend on entrainment, which is a complex phenomenon affecting various disciplines, from physics to human physiology. From the biomusicological point of view, entrainment is an organism’s ability to synchronize movements in the presence of an external rhythmic stimulus. Thus, although music is the most studied and complex source of coordinated movements, entrainment is a very common biological occurrence that does not depend on music or musical rhythm only, but also transpires in a great number of acoustical and nonacoustical events (Phillips-Silver, Aktipis, & Bryant, 2010). Consequently, the synchronization required for interaction in musical environments must be considered as a particular case among various other forms of movement coordination found in musical and in nonmusical environments. This could lead to the investigation of the role of entrainment as an overall human–computer interaction theme in the production of human choreographies in interactive spaces.

The paper’s topic is introduced in a theoretical background section, where the fundamental principles of bodily interaction are presented. Blending theory, spatial reasoning, implicit knowledge, and entrainment in its many forms and characteristics are considered the fundamental cognitive processes that govern a user’s behavior in an interactive space. These concepts constitute a set of analytical tools whose reciprocal interrelations form a dynamic system continuously fed by the user’s experiences, which must be regarded as the main agent of the user’s interaction in such environments. Two music analysis subsections focus on rhythmic structure organization and recursive patterns, which primarily influence selective entrainment in musical environments. Harmonic Walk, a motion-based music application

aimed at the knowledge and practice of tonal harmony, is presented as a useful case study. User movements were analyzed to better understand the relationship between musical structures and human choreographies. Finally, emerging design issues are presented and discussed.

THEORETICAL BACKGROUND

Motion can be described as the kinematic relationship between two points in space. Usually, this relationship involves various concepts of physics, such as displacement, distance, speed, acceleration, and so on. When related to a user's change of position in a musical interactive space, motion implies the existence of the following three conditions:

- (a) the spatial positioning of interactive landmarks,
- (b) a reason to choose one interactive landmark target instead of another (i.e., where to move), and
- (c) a reason to move from one interactive landmark to another (i.e., when to move).

Spatial Positioning of Interactive Landmarks

In motion-based applications, there is a strong relationship among a physical space, a user's spatial cognition, and digital contents. Thus, a tool is needed to link these aspects and to manage them in a successful way. An example is provided by *Stanza Logomotoria* (Zanolla, Canazza, Rodà, Camurri, & Volpe, 2013), a motion-based application aimed at linking a narrative content to sounds. The camera system employed by this application covers a 4 x 3m rectangular floor area. Depending on different purposes, the *Zone Tracker* application partitions this surface with several masks.² Each mask provides a generic spatial organization with a number of available landmarks regarding where the content (e.g., audio files, digital sound processing effects, or music composition algorithms) are positioned. The spatial positioning of interactive landmarks may be visible or invisible to the user. When visible, interactive landmarks may be labeled by visual tags or visualized through graphical elements projections. However, the available landmarks must be connected to the content through a spatial organizing principle. This is provided by the conceptual integration between the spatial characteristics of musical features and the actual space. Conceptual integration is a term borrowed from blending theory (Fauconnier & Turner, 2002), which is a framework for human knowledge that suggests the brain constructs information through various forms of integration between two input spaces. The theory defines a four-space model: a generic space, two input spaces, and a resulting blended space. As applied to our research, the generic space is where abstract knowledge about the musical feature is stored. The Input Space 1 is the physical space where interaction happens; the Input Space 2 provides the spatial organization of musical concepts. The resulting blended space is a spatial projection that takes the characteristics from both input spaces to create something completely new (Benyon, 2012). The conceptual blending theory forms the base of many design approaches, for instance in learning applications, where a user's first-person embodied experiences are used to model physics-related events in augmented-reality environments (Enyedy, Danish, & DeLiema, 2015). In the case of motion-based musical applications, the physical space is

matched with the musical concept upon which the application is based (see Figure 1). The relationship between these two input spaces is mediated by a geometrical representation of musical concepts and their spatial projections (Mandanici, Rodà & Canazza, 2015), which provides the sound positions (or sound-processing zones) in the new blended space.

Many musical features, such as harmony or melodic movements, historically have been illustrated by spatial representations. Examples of this kind of representations are Euler's *tonnetz*, which literally means "web of tones" and is a spatial schema showing the triadic relationships upon which tonal harmony is based (Euler, 1739); the neumatic notation of Gregorian chant (Strayer, 2013); and chironomy (Carroll, 1955), a gestural system expressing melodic contour variations. These suggest the idea that the spatial positioning of sounds conveys some meaning about their inner nature and element organization and that this meaning can be made available to the user through spatial representations, as can be seen in the modern *tonnetz* shown in Figure 2.

Where to Move

In order to move in space, a user needs to know where to go. That means that s/he must be informed of where her/his target interactive landmark is. While this information typically is obvious in everyday life, when people's motion is usually directed to well-known, precise goals, the same cannot be said about a target interactive landmark in an artificial environment. In such a situation, motion implies the creation of a cognitive map by the user, which includes landmarks, way finding, and route segments (Montello, 2001). However, a cognitive map is much more than a simple mental-routing sketch: It includes other nonspatial elements, such as perceptual attributes, emotions, and the system's feedback. Indeed, the creation of the new blended space allows the user to navigate concepts in the physical space and to move literally inside them, obtaining a different audio feedback according to the occupied zone.

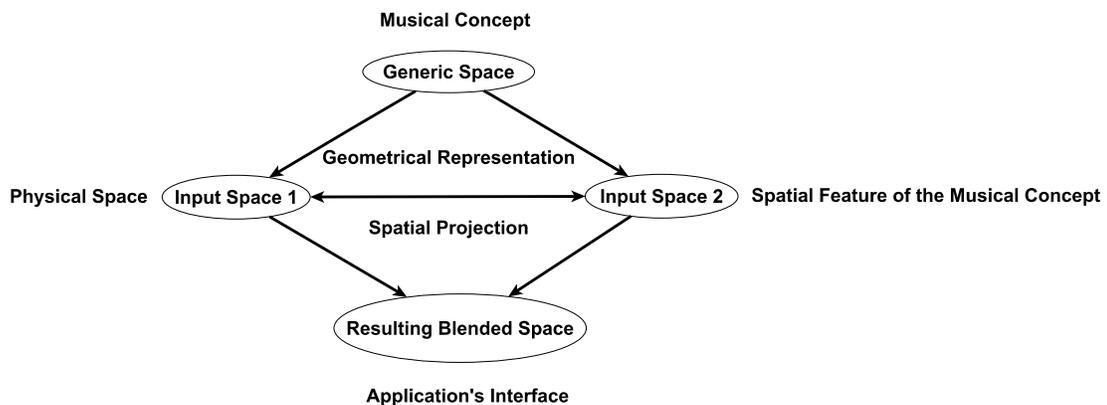


Figure 1. Conceptual blending diagram, adapted from Benyon (2012, p. 223). Starting from the generic space of the musical concept, a conceptual integration is operated between the physical space and the spatial feature of the musical concept. The resulting blended space is represented on the application interface.

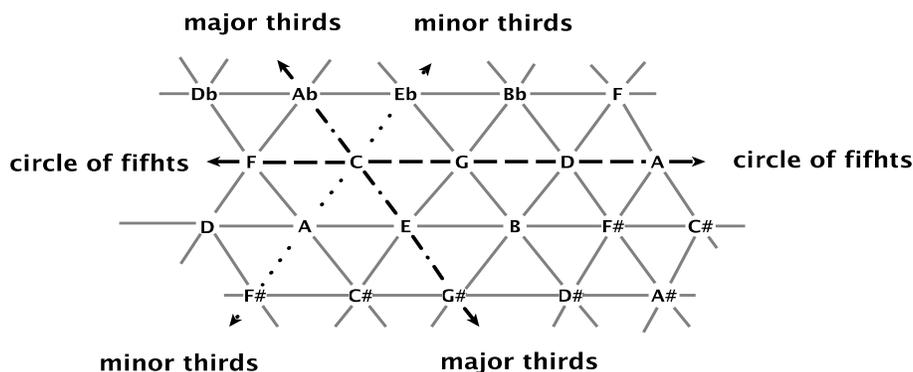


Figure 2. The modern *tonnetz* showing the axis of the circle of fifths (horizontal black dashed line), the axis of minor thirds (diagonal black dotted line), and the axis of major thirds (diagonal black dashed and dotted line). Each chord is formed by the three pitches at the triangle's vertices, and each contiguous triangle (chord) shares at least two pitches with its neighbor. The chords represented by triangles with just one vertex point, have only one note in common. This represents different grades of chords commonalities (Cohn, 1997), which, through the *tonnetz* spatial representation, are expressed in a very concise and efficient way.

When applied to music-related research, the coupling between spatial location of concepts (interactive landmarks) and musical-content perception begins to feed the user's cognitive map of the environment, which then drives her/his decisions on where to move in the artificial environment. This coupling also is driven by the implicit knowledge of musical language, which is a well-known mental process that allows the unconscious acquisition of very complex and structured constructions. The mind is continuously fed by structured stimuli (speech, music, spatial relationships, sensorimotor information, etc.) and, independent of the user's will, builds an inner knowledge about them (Reber, 1989). As an example, considerable research in the field of music psychology offers evidence that children as young as 4 and 5 years of age (e.g., Corrigan & Trainor, 2010) have wide, implicit harmonic knowledge: They comprehend chord functions, harmonic relations, and perception of regularities of harmonic frames in time. Because tonal music is ubiquitous in the Western music cultural environment, all these characteristics are learned from mere passive exposure (Tillmann, Bharucha, & Bigand, 2000) and so can be considered a cognitive skill common to users who have been exposed to that musical tradition, independent of her/his degree of musical education. Thus, when a user enters a musical interactive space, her/his implicit musical knowledge is elicited by the audio output and can so be accessed, used, and/or modified by the user during the experience and can inform responses regarding where to move within the interactive space.

When to Move

We have already stated that a user's implicit knowledge includes musical language structures and spatial cognition. A third important element to consider is entrainment, which is the process responsible of "when" to move in the interactive space. According to Thaut, McIntosh, & Hoemberg (2015, p. 1), "Entrainment is defined by a temporal locking process in which one system's motion or signal frequency entrains the frequency of another system." In physics,

entrainment is the frequency alignment of two oscillating bodies on phase or at 180° out of phase. It happens because small quantities of energy transfer from one body to the other until they are fully synchronized. In human beings, the firing frequency of auditory neurons when receiving an external rhythmic stimulus influences the firing frequency of motor neurons, causing over time a coordinated movement (Thaut et al., 2015 p. 2). This resonates with the model of entrainment proposed by Phillips-Silver et al. (2010), according to whom entrainment is composed of three phases:

- (a) the rhythmic detection of environmental signals (not only acoustic but also as a byproduct of biological phenomena),
- (b) the ability to produce rhythmic signals (not only deriving from musical activities but also from other biological activities), and
- (c) the ability to integrate both proceeding phases in order to adjust the output's rhythm.

The main point of this framework is that it does not limit the idea of entrainment to the basic, regular pulse synchronization generally observed when people clap their hands to their favorite song's beat in public concerts, when music players align their individual timing on the conductor's gesture, or when dancers perform the same movement in a strictly rhythmic fashion. Rather, it extends the entrainment range towards a more general and wider number of events, such as environmental signals (seasonal or day/night alternation, weather changes, wind blowing, sea waves crashing) or biologically produced rhythms (e.g., breathing, eating, heart beating, walking, crickets' chorusing, wolves' howling). Many living beings' actions depend on various forms of entrainment with these signals, in both natural and artificial environments. These examples emphasize at least three important aspects of entrainment:

- (a) Entrainment may occur in conditions very different from regular rhythmic input (predictive entrainment);
- (b) Entrainment is connected not only to "when" to move, but also to "why" to move (selective entrainment); and
- (c) Coordination is the condition of success in the activity.

Predictive Entrainment

The framework of entrainment proposed above is useful for understanding synchronization in nonmusical reality-based interaction environments, which employ smartphones, tablets, touch screens, interactive walls, and so on. In daily life, synchronization is fundamental to coordinating physical efforts and in helping human communication. Thus, the analogy between real life and digital content, which characterizes such interactive spaces (Jetter, Reiterer, & Geyer, 2013), suggests that synchronization could also play a similar role in the design of applications based on such devices. However, to understand how entrainment works in a musical interactive space, it is necessary to focus not so much on rhythmic input regularities, which can be found in both natural and artificial environments, but rather on rhythmic predictability. For example, an isochronous rhythm has a high degree of predictability because it has an intrinsic regular nature. Nonetheless, a slowing pulse (*rallentando*) is predictable to some degree, because a listener can follow a previously stored model of *rallentando* and try to adapt it to the current event sequence (Friberg & Sundberg, 1999). Another example of how humans can adapt entrainment to particular situations is the case of "soft entrainment," which

occurs when small deviations in rhythmic entrainment among different performers in music ensembles are registered. Soft entrainment may occur at various degrees of deviation, depending on the phase of the musical phrase. Yoshida, Takeda, and Yamamoto (2002) reported that synchronization is maximal when musicians aim at the phrase's climax (tense phase), whereas it deviates more often when approaching the phrase's end (relaxing phase).

These examples show that entrainment is a dynamic process that involves not only mere beat detection but also a much wider range of musical elements, such as expressive trends, motion patterns, and musical phrase organization. Jones and Boltz (1989) provided an extensive framework of how real-world timing structures are organized in a hierarchical way, thus allowing predictive entrainment to work. They affirmed that the distribution of many natural events' markers is nested at several timing levels that are consistent with ratio or additive timing transformations. This explains not only why humans can entrain with natural phenomena, such as gradual or abrupt changes of velocity, but also how prediction works when they have to synchronize with multilevel, hierarchically organized time events. For example, musical metric structure starts from a lower level, composed by the smallest rhythmic units and, through successive layers of stratification, reaches more extended musical units, such as musical periods, forms, sonatas, or symphonies. A hierarchical organization such as this allows a subject to have an idea on how musical events are organized and to make a prediction regarding how long s/he has to wait until the expected event occurs. Yet, a wider look at musical entrainment also needs to include the observation that not all kinds of music are strictly based on isochronous pulse. Similarly, not all the parts of a beat-based music are rigorously dependent on beat. To set an example, think about a classic concert's cadenza, where the soloist leaves the overall ensemble governing pulse, to play freely and express her/his virtuosic ability. In the same way, in the Gregorian chant's swinging gait, a pulse can sometimes be perceived, but always among many breathing pauses and fermata.³ There are also types of beat-composed music where the pulse is not perceivable at all in the musical output. This is the case of many classical contemporary music compositions, such as Ligeti's (1966) *Lux Aeterna*, one of the most popular works of this genre, where the lack of periodic repetitions in the rhythmic pattern prevents any metrical organization of musical elements.

Notwithstanding, all the cited examples show a high degree of predictability in that, even if the events are not subjected to a regular metrical organization, they show some shared musical or nonmusical pattern. In classical music solos and concertos for solo and orchestra, the solo's cadenza is marked at its beginning by a precise fermata on the second inversion of the I degree at the beginning and by a conclusive dominant chord in root position at the end.⁴ Thus, two harmonic markers act as strongholds of the relatively beat-free event, allowing the conductor and the whole orchestra to resynchronize their beat at the end of the cadenza. In Gregorian chant, the predictive timing of events is given by the breathing times in the musical phrases, whose code is deeply grounded in physiological, expressive, and melodic structure cues.⁵ Chaotic mass movements produced by very small musical elements are the result of composition techniques based on mathematical and physical models employed by many 20th-century composers. In Ligeti's micropolyphony, for example, tendency masks rule the rhythm, density, and pitches of the musical elements (Drott, 2011). The temporal evolution of a tendency mask is perceived by the listener in biological and physics terms, such as growth, proliferation, thickness, fluctuation, and so on. Thus, process endpoints are perceptual landmarks that can be regarded as predictable entrainment anchors.

Selective Entrainment

In this paper, we call *selective entrainment* the subject's ability to focus her/his synchronization activity on a specific environmental signal chosen from among multiple simultaneous rhythmic stimuli. It is easy to notice that, in natural environments, it is common for acoustical or nonacoustical signals to overlap. For example, it is not difficult to imagine that a hunter has to select her/his prey's biological signals from among all the other signals in the natural environment in order to be successful in the chase. Hence, in a musical interaction event, the subject has to filter the incoming signals to focus on a specific input, depending on the goal s/he wants to achieve. This means that movement is triggered by some environmental changes that the subject is interested in, and that movement depends on the perceptual timing of these changes. Thus, when to move is strictly connected with why to move and the reason to move is the need to remain tuned into important environmental events. This entrainment mechanism, involving contextual awareness and prior skills, is probably one of the most important abilities that a user brings to the digital space (Jacob et al. 2008, p. 2) and which highlights one of the most effective analogies between real-life environments and interactive spaces. Whereas the reacting to environmental signals may have important biological consequences in the physical world, it acquires a completely different meaning in artificial interactive spaces, where signal flow is controlled and where the user's responsiveness is one of the fundamental aspects of the application design. First of all, if the interaction logic is controlled by the designer, the reaction to the signals is always mediated by implicit knowledge of the user on which the designer can make assumptions based on her/his experience or intuitions. Second, in the case of multilevel signals (e.g., musical input), the user is asked to apply a selective entrainment as s/he decides at which level to synchronize her/his movements with the input. The general idea about entrainment in artificial environments is that movement is always the result of a cognitive-selective process related to previously acquired knowledge. The consciousness about where to point her/his attention is the key element of selective entrainment: How can designers help users in achieving this goal remains a great challenge in reality-based interaction design.

Cognitive Meanings of Coordinated Movement

No entrainment activity, whether in a natural or artificial environment, would be successful without coordinated movement. Coordination may have different degrees of accuracy, as in the already cited case of soft entrainment. Nevertheless, it is clear that the success of action depends on the subject's ability to detect the right rhythmic input and to align her/his behavior to it. Baimel, Severson, Baron, and Birch (2015) underscored how behavioral synchrony in collective activities fosters social coordination and empathic concern, stressing how the outcome of attuning the minds of a group helps its individuals develop abilities. Moreover, Clayton, Sager, & Will (2005) observed that cognitive activities, such as perception, attention, and expectation, depend on entrainment, and that musical entrainment, in particular, helps motor- and self-control development in individuals. These observations foster the idea of entrainment as a general cognitive skill that coordinates the relationships between humans and the world's events. Considering entrainment in an interactive space, the framework from Phillips-Silver et al. (2010) cited above could be reinterpreted in the following way:

- (a) The rhythmic detection of environmental signals represents the openness of the subject to receiving information from the system producing the signals;
- (b) The user's ability to produce rhythmic signals means that s/he is able to respond to the signals produced by the application and that s/he understands the interaction mechanisms; and
- (c) The ability to integrate both the preceding phases to adjust the output's rhythm establishes the point in which the user's response is aligned with the system's output, confirming that a cognitive relationship is established between the user's motion and the principles upon which the application is based.

Rhythmic Structure of Music

Music is the most powerful source for entrainment because it is based upon a high degree of element organization. The most structured form of music–movement coordination is dance, where single movements or combinations of movements (choreographies) are arranged to follow the musical structure. There are popular dances where movements are rigidly entrained by the steady rhythms and by a simple formal organization of the music. Two examples of this are the traditional Quadrille⁶ and the folkloristic dances, such as the Cheraw dance or Tinikling,⁷ where not only the dancers' movements but also the dancers' available space is timing-locked by entrainment.

It is not clear why isochronous pulse is so pervasive in many kinds of music. However, the perceptual link between the musical pulse and a fundamental biological element such as the heartbeat could perhaps explain why the role of beat is so important for the organization of musical elements. Nevertheless, it seems that, even when exposed to nonisochronous auditory stimuli, such as Hindustani classical music, subjects respond with an isochronous motor response (Will, Clayton, Wertheim, Leante, & Berg, 2015), as if the need to adapt the auditory stimulus to a previous embodied sense of beat was a necessary perceptual condition. The first level of beat organization in Western music starts from the definition of the musical meter, which depends on the occurrences of melodic elements along the beats timeline. Generally, beats can be grouped into binary or ternary tempi. Every rhythmic unit is further grouped into semiphrases, phrases, and periods, as showed in Figure 3. This hierarchical organization also allows for the detection of other musical elements, such as, for instance, the harmonic rhythm, which depends on the duration of the various harmonic regions. A harmonic region is a musical excerpt that can be harmonized by one musical chord. The chord's change determines the duration of the various harmonic regions and hence the harmonic rhythm.

Recursive Structures in Music

Music is characterized by hierarchical structures that are organized in various overlapping layers, expanding from a fundamental, deep structure to reach the complete score level (Schenker, 1979). The collaborative work of music theorist Fred Lerdhal and linguist Ray Jackendoff produced a theory of tonal music organization that showed the commonalities between the structure of

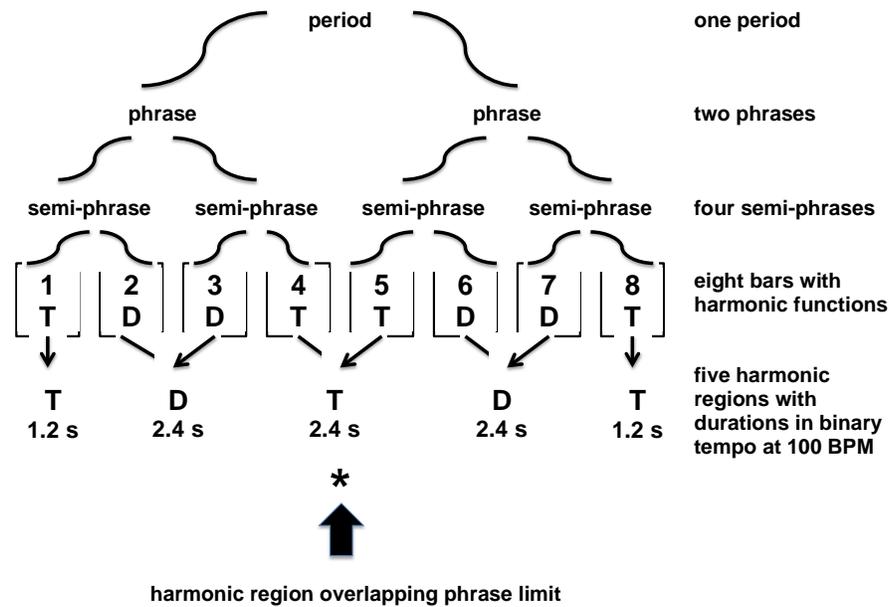


Figure 3. Formal organization of a typical music period with phrases, semiphrases, bars with harmonic functions, and harmonic region durations. In this musical period, the second harmonic region gathers bars Number 2 and 3, which share the same harmonic function (D, dominant). The same happens for bars Number 4 and 5 (tonic function) and for bars Number 6 and 7 (again dominant). As shown in the lower part of the diagram, the extent of the harmonic functions does not correspond to the formal structure of the period. Thus, the harmonic regions (1 + 2 + 2 + 2 + 1 bars) form a perceptual structure that is superimposed to the formal organization of the period and that establishes a new level of the selective musical entrainment.

musical phrases and periods and the structure of linguistic sentences (Lerdahl & Jackendoff, 1985). The linguistic sentence tree structure (i.e., diagram), formed by articles, nouns and pronouns, verbs, prepositions, adjectives and adverbs, conjunctions, and interjections, is similar to Lerdahl and Jackendoff's hierarchical tree of musical elements grouping, metrical structure, time-span, and "prolongational reduction." This framework is based on the concept of recursion, which is the repetition of the same pattern at different levels and time scales. As an example, the hierarchical organization of an English sentence is compared to a musical phrase (see Figure 4) showing respectively linguistic and harmonic recursive elements.

Harmonic recursion also plays a fundamental role in harmonic progressions, which are very common, repetitive harmonic patterns used in traditional and popular repertoires. The key concept in tonal harmony is that chords are organized in a hierarchical order where the tonic, dominant, and subdominant chords (i.e., the I, IV and V degrees) play a primary role, whereas chords built on the II, III and VI degrees (i.e., parallel harmonies) play a secondary role. Thus, starting from its simplest form T-D-T (corresponding to the harmonic structure of Schenker's, 1979, *ursatz*⁸) it is possible to expand primary chords with their parallel harmonies to create many alternative harmonic progressions. In Figure 5, the squares represent primary chords and the smaller rectangles are the parallel chords. The diagram shows examples of harmonic progressions obtained by adding parallel harmonies to the IV and I primary chords.

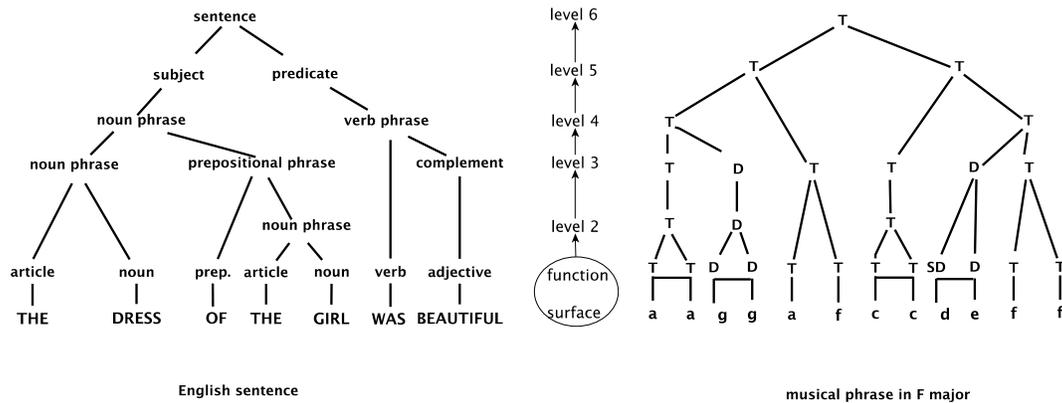


Figure 4. An English sentence and a musical phrase presented as six-level syntactic trees. The left area of the figure presents the English sentence tree. It provides a surface level (i.e., words with their linguistic functions), whereas the right part shows the musical phrase tree with its surface level (i.e., pitches with harmonic functions; the lowercase letters represent the musical note, and the designations of T, SD, and D are the tonic, subdominant and dominant harmonic functions, respectively). Five other structural levels are shown with related recursive patterns. In the sentence tree recursive patterns can be found at Levels 2 (the girl), 3 (the dress), and 4 (the dress of the girl). Something similar happens in the tonal harmony functions of the musical phrase when observing the recursive occurrence of the main harmonic relationship, the dominant-tonic (T-D) and tonic-dominant (T-D) harmonic links.

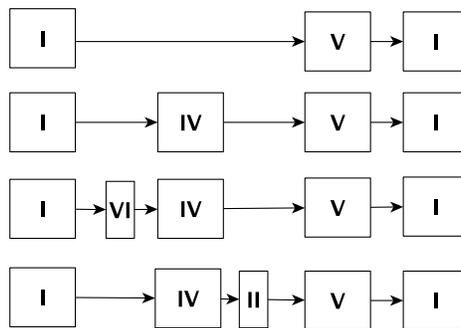


Figure 5. Examples of common harmonic progressions. The Roman numerals represent the musical chords. The square boxes are the fundamental harmonies (i.e., I = the tonic, V = the dominant, and IV = the subdominant degrees) and the rectangles represent the parallel harmonies (i.e., II = the supertonic and VI = submediant degrees). The arrows show how the various chords are connected to each other.

A CASE STUDY: HARMONIC WALK

In the previous section, a theoretical background on motion and musical structures has been presented and analyzed in defining a framework to understand the elements that trigger movements in musical interactive spaces. The aims of this section are (a) to link the formal characteristics of music to movement patterns derived from a user’s motions in such environments, and (b) to show how such structures shape human behavior during a user’s interaction with musical content. Harmonic Walk has been chosen as a case study because it is based upon one of the most

complex and structured features of Western music: tonal harmony. In the next subsections, some motion patterns derived from musical structures are presented, analyzed, and discussed, taking also into account the design optimization of the application.

The Application's General Outline

Harmonic Walk (Mandanici, Rodà, & Canazza, 2016) aims at allowing users to experience highly structured musical features through full-body movements in space. It has been designed as a music-learning environment to be applied in teaching music harmony at various ages. Beyond the discovery of several important musical structures, such as chords and harmonic rhythm, the application leads the user to accomplish a complex musical task, such as melody harmonization, in an easy and handy way.⁹ This is achieved through the adoption of a very simple interaction modality: steps through which the user links the various interactive landmarks.

Related Work

A system similar to Harmonic Walk is Harmony Space, designed at the Music Computing Lab of Stanford University (Holland, 1994). The Harmony Space interface is a desktop two-dimensional matrix of pitches that allows the performance of musical chords. The environment is rich and complex and, although it has been designed for learning purposes, it fits an expert-user's level as well. More recent systems, such as Isochords (Bergstrom, Karahalios, & Hart, 2007) or Mapping Tonal Harmony,¹⁰ are also complex environments that require a high degree of knowledge and employ some representation of the harmonic space on a two-dimensional computer screen. Regarding the use of responsive floors for harmonic space representation,¹¹ an example is provided by Holland himself, who tested a physical space extension of his Harmony Space by adding a floor projection and a camera tracking system (Holland et al., 2009). Harmonic Walk has been compared to rhythm games such as Dance Dance Revolution,¹² where the user is trained to follow a musical input through visual stimuli. In this game, repeated patterns help movement memorization in a rather mechanical way, independent of the musical features. Harmonic Walk, on the other hand, fosters musical listening and selective entrainment by inviting the user to direct her/his attention to a precise musical target (e.g., harmonic rhythm, musical phrases, a song's beat).

System Architecture

Harmonic Walk employs a ceiling-mounted camera to track the presence and movement of a single user on the floor surface within camera range. Typically, the camera is mounted 3 meters above the floor, which results in a defined rectangular floor surface of 3 x 4 m. The system is composed of two software modules—one for motion data analysis and processing (the Zone Tracker application) and the other for sound production (the Max/MSP patch¹³) connected through the OSC protocol (Wright, 2005). The system combines motion data with a mask for surface division and for positioning interactive landmarks. As soon as a user enters the Harmonic Walk area, the system detects the zone occupied by the user and sends this information to the Max/MSP patch that provides the audio output.

Harmonic Walk Experimental Method

A formal test was organized at the Barbarigo Institute in Padova, Italy, in December 2014, with the aim of measuring the power of Harmonic Walk in the field of musical education. The test was carried out with 22 high school students between 16 and 22 years of age, equally subdivided between musicians and nonmusicians, based on whether they were attending a music-based curriculum or a traditional academic curriculum. The popular song “Il ragazzo della via Gluck,” by the Italian singer Adriano Celentano,¹⁴ was chosen because of its clear harmonic structure. During the test, only the first phrase of the song was employed. This musical excerpt is composed of 11 harmonic regions built upon 3 chords all belonging to the same key.

The Three-stage Approach

The ultimate aim of the Harmonic Walk application is to drive the user towards a tonal melody harmonization, which is a complex multifaceted task for the user. Melody harmonization can engage the user in at least the following three subtasks:

- (a) detection of the harmonic rhythm of the melody,
- (b) knowledge of the harmonic space of the melody, and
- (c) choice of the chord sequence that can fit the melody.

To check the user’s level of awareness about these three aspects of melody harmonization, a three-stage experimental approach was conducted.

The high school students were tested individually in private sessions where only the music teacher and the test conductor were present. Students were provided with some written instructions about the task to be accomplished and with a short demonstration about the interactive space and the interaction modality. No previous information about the song used in the tests was given to the students.

First Stage: Detection of the Harmonic Rhythm of the Melody

The spatial positioning of the interactive landmarks for the detection of the harmonic rhythm of the melody began with the analysis of the perceptual image of a melody by a user. A melody is perceived as a sequence of events (notes) organized on a timeline. The perception of melodic patterns and implicit chord sequences makes the user organize the various notes according to a metrical and harmonic frame (Povel & Jansen, 2002). In our research, this process produced a segmentation of the composition into different harmonic regions, which, in case of one key melody, were all part of the same tonality. To make the Harmonic Walk user aware of this process, we excerpted the song’s audio file where harmonic changes took place, and we assigned each harmonic region to a subsequent target landmark in the interactive space. Adopting the Zone Tracker surface mask depicted in Figure 6(a), the harmonic regions were laid one after the other along the surface’s borders (see Figure 7 for the tag position of the song excerpt used in the experiment). This representation addressed the idea of a conceptual integration between the music structure and the spatial organization of the interactive landmarks discussed above.

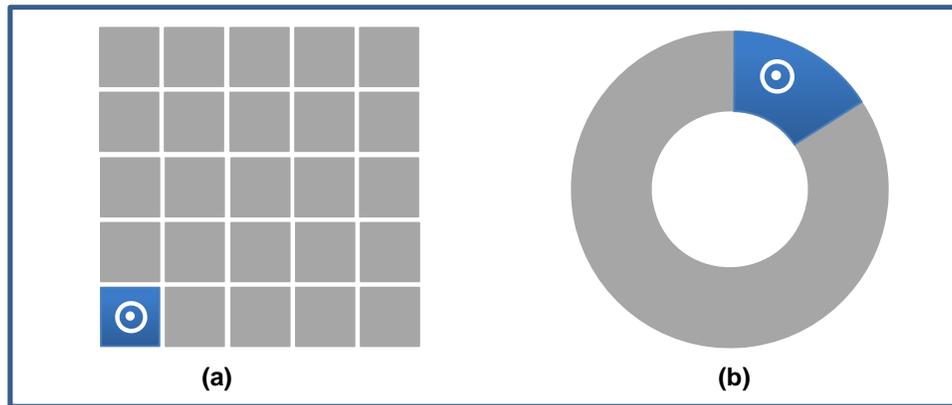


Figure 6. The two masks for the floor division in the Zone Tracker application as applied to this Harmonic Walk research. From left to right: (a) a 25-squares zone partitioning, designed for the harmonic changes interaction, with a dark square designating the area activated by a user’s presence; and (b) a ring with six areas for song harmonization, with the dark area showing the space activated by a user’s presence.

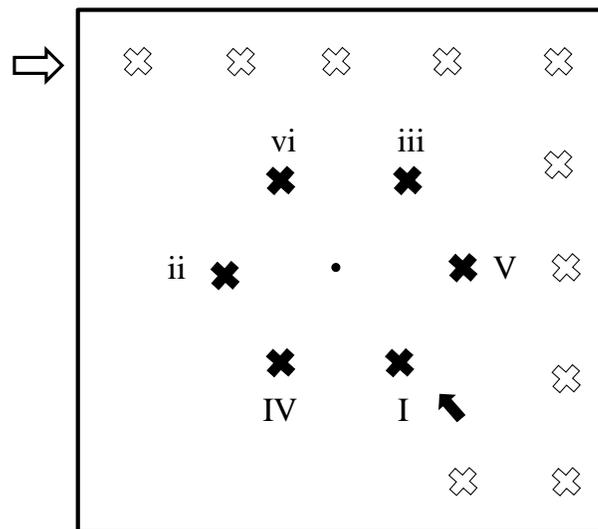


Figure 7. Visual tags of the harmonic regions sequence (white crosses) and of the six chords of the tonality harmonic space (black crosses, with the fundamental roots, uppercased) and the parallel roots (lowercased) employed in the formal tests of Harmonic Walk. The arrows indicate the starting positions.

Moreover, in this stage of the research, the user did not need to worry about where to move because the only possible direction was along the tagged path. In the test, the user was asked to link the harmonic regions by stepping to the next position in time with the harmonic change. If s/he was ahead of it, the audio fragments overlapped; if s/he was late, the song was interrupted. However, successful accomplishment implied that the user recognized the harmonic rhythm changes and that s/he was able to apply a selective entrainment to decide the exact moment for moving towards the next song’s excerpt in a seamless manner.

Second Stage: Knowledge of the Harmonic Space of the Melody

The spatial organization of interactive landmarks for the exploration of the harmonic space and for melody harmonization derives in a straightforward way from tonal harmony theory (Piston, 1962). A tonality harmonic space is formed by three fundamental (I, IV and V degree) and three parallel (II, III and VI degree) roots. These six chords have meaningful spatial relationships, as shown in the *tonnetz* representation of Figure 8. To make this spatial disposition available to the user, we employed the circular surface mask depicted in Figure 6(b) and laid the 3 fundamental roots in one half of the ring and the 3 parallel roots in the other, following the same order as in the *tonnetz* representation (see Figure 7 for fundamental and parallel root disposition on the responsive floor). In the test, the user was asked to enter the ring and freely explore the harmonic space by trying to link the chord sounds to their spatial disposition. Each musical root in the tonality of C major was synthesized using four different wave shapes mixed to form a uniform sound. In this case, the problem of directing the step (i.e., where to move) and when to change to position may have been biased by many factors because both decisions were left to the user.¹⁵

Third Stage: Melody Harmonization

For this third task, we used the chord spatial positioning described above. The user was asked to sing the same song chosen for the first stage of experiment (sometimes with the help of the teacher) and to follow its harmonic rhythm in deciding when to move. Moreover s/he had to decide which chord sequence better fit the song's melody (i.e., where to move) and to combine these two pieces of information in deciding the move. The required movement was rather complex and the timing was very strict. In this case, not only was selective entrainment necessary for focusing on the harmonic rhythm durations, but also predictive entrainment was useful to the subject in preparing the step direction. We assigned 5 minutes to each student to complete the harmonization task. If in this period of time the student was able to identify at least the first seven chord positions useful for the melody harmonization, the task was considered successful.

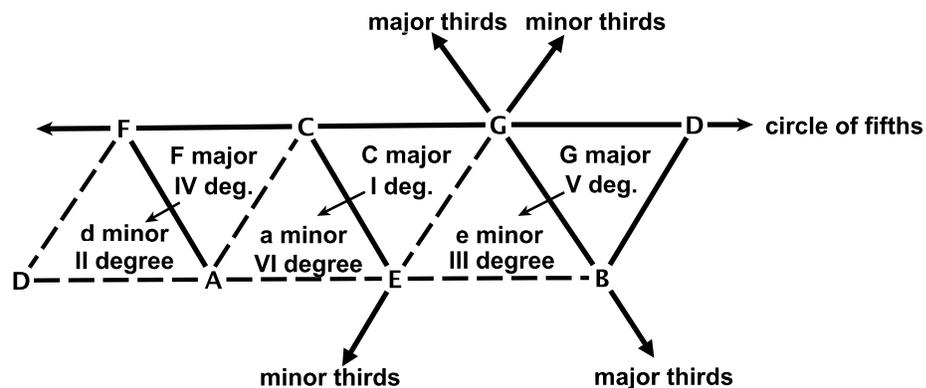


Figure 8. *Tonnetz* representation of the six roots of the C major tonality space, with the three fundamental roots (solid lines) and the three parallel roots (dashed lines).

Results

At the completion of the first stage of our research, to verify whether the subjects were aware of the harmonic changes that occurred in the first phrase of the song, we provided them with the written words of the song and asked them to underline the syllables where they remembered the harmonic changes happening. The song contained 10 harmonic changes, corresponding to 10 syllables. The average of number of correct harmonic changes detected was 3.6 for nonmusicians and 5.5 for musicians. As can be observed in Figure 9, there was a trend of decreasingly correct answers in the identification of harmonic changes as the song progressed. This could be related to memorization problems or to the fact that the latter part of the phrase contained more complex harmonies.

The second stage of the testing was an exploratory phase with no defined task to perform other than for the subject to investigate chords and their spatial setting within the interactive space. Our observations of users' behaviors are reported below.

The third stage aimed to assess the subjects' ability to identify harmonization. The number of subjects who could complete successfully the song harmonization task was just 1 among the 11 nonmusicians but 5 among the 11 subjects in the musicians group. These results show that results show that the simple use of Harmonic Walk, even without providing explicit information to the test subjects, is capable of introducing the students to a complex experience like that of melody harmonization leveraging only on their implicit knowledge of Western tonal harmony. A fuller report and discussion of the collected data and findings can be found in Mandanici et al. (2016).

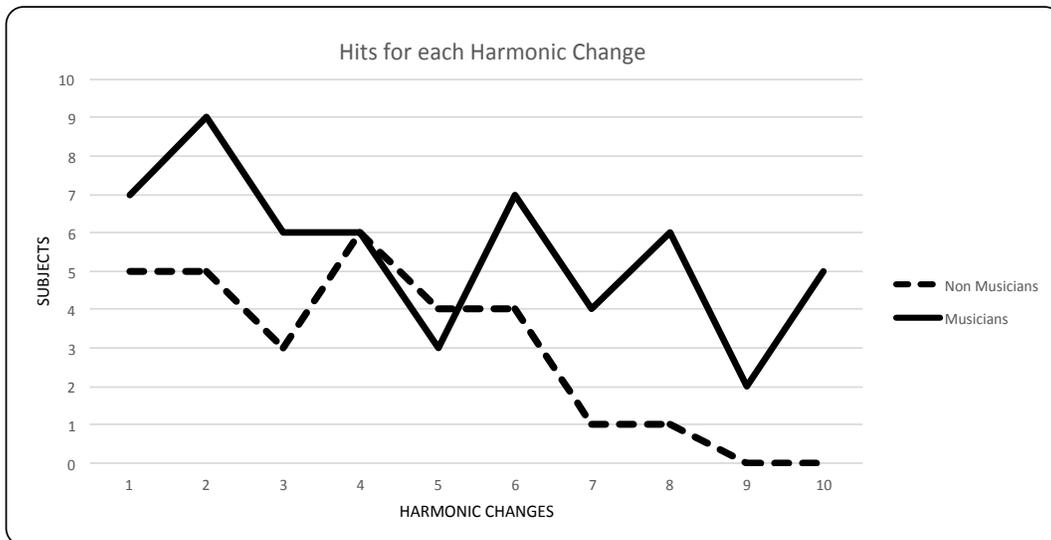


Figure 9. Diagram of hits of the 10 harmonic changes of the first phrase of “Il ragazzo della via Gluck” by the Italian singer Adriano Celentano, as detected by the musician and nonmusician subjects. The number of hits decreased considerably for both groups from the beginning toward the end of the song’s phrase.

Harmonic Walk Experimental Observations

Beyond the formal test session presented above, a preliminary experiment of Harmonic Walk was carried out in the spring 2014 in the elementary school of Paderno Franciacorta (Brescia, Italy). The aim of this test was to verify whether children could locate different chords scattered within the interaction space, remember these positions, and find one or more paths to link them (Mandanici, Rodà & Canazza, 2014). The test involved 50 children, aged between 5 and 11 years. In addition, the Harmonic Walk was tested in an informal experimental setup with adults during the Researchers' Night at the University of Padova (Italy) in September 2014, as well as in several music classes in the above-cited elementary school in 2014. Although both the preliminary testing and the informal tests involved different types of music and processes to assess the subjects' understanding of harmony, each was in line with the overall goals (i.e., harmonic rhythm interaction, exploration of the harmonic space, and melody harmonization) presented within the formal testing procedures.

Below, we report several observations about the users' behaviors during the various experimental test sessions (preliminary, informal, and formal). These observations focus on the users' movements in relation to the structure of the musical elements and to the synchronization mechanism required by the task.

Harmonic Rhythm Interaction

The harmonic rhythm interaction required the user to make a step forward when s/he detected a harmonic change. In general, the resulting movement quality was stiffness; it occurred when users related musical harmony in a rather unnatural way. We believe this outcome is related to the musical quality of the song employed in the formal test described above. For example, in one informal test session, we employed instead the first five bars of Beethoven's *Symphony No. 5*, where two harmonic changes are marked by a musical *fermata* (see Figure 10). At these two points (bars 2 and 5), users were facilitated both in the detection of the harmonic changes and in the step movement. In reality, the required synchronization at these two points is much simpler as a result of the *fermatas*, which allow a much longer release time as compared to typical synchronization times. This is an example of how the musical rhythmic structure can influence the harmonic rhythm interaction.



Figure 10. First five bars of the piano reduction of Beethoven's *Symphony No. 5*. The long release time of the two fermatas at bars 2 and 5 require a much simpler synchronization mechanisms with respect to a stricter pulsed time.

Exploring the Harmonic Space

For each Harmonic Walk test, we provided an exploratory phase (second stage of the formal test described above). The following behaviors were observed:

1. Running along the ring. During the informal tests with the elementary school children, the exploration of the harmony was created by tones being presented audibly as the children moved to the interactive landmarks along the ring within the presentation space. Children aged 5 or 6 years were attracted to the sound produced by the ring and simply ran continuously both clockwise and counterclockwise to hear the effect. This observation shows the great communicative power of interactive environments, which have a very strong influence on the younger subjects.
2. Walking along the ring. Adults and high school subjects, when asked to explore the environment, simply walked along the ring. This behavior expresses the influence of the shape of the chord disposition on the users' behaviors. Harmonic progressions have hierarchical relationships that are not represented in the chord disposition. Thus, the user may assume that following the circle would lead to some useful musical information about the harmonic space, but soon realizes that it is not so.
3. Performing elementary harmonic progressions. Some older users, frustrated by the unsatisfying musical result of the simple circular walk, tried other exploratory strategies by linking only two or three chords at a time. This is a more fruitful approach in that it involves an important exploratory element: listening. While listening, the user can apply her/his implicit knowledge of tonal harmony, which can in turn drive her/his movements. Listening is especially important during the exploratory phase because the user needs to learn to synchronize her/his movements with what s/he perceives from the external environment. Thus, if some strong harmonic relationship is recognized, this allows her/him to stop at that point and repeat the route, thus reinforcing the gained understanding.
4. Exploring newfound progressions following a metrical structure. The harmonic progression path repetition makes the user increasingly confident about which path to follow in the balance of the test, thus allowing some metrical entrainment to emerge. Harmonic progressions organized into a metrical structure open the door to new creative behaviors because they allow new, richer, and original chord progressions to be performed. These can be the basis for new tonal music compositions completely originated from bodily movements.

Melody Harmonization

The melody harmonization tasks described above required the user to perform a true choreography, with a fluent and sometimes elegant but highly constrained motion among the various chord locations. Every user exhibited her/his own motion style while performing a song harmonization, as observed by Holland et al. (2009) in similar conditions. Indeed, it seems that, in spite of its motion constraints, the application was able to evoke in the users the long-term sensorimotor information that characterizes personal movement qualities. Further

observations during the tests showed that the ability of completing the melody harmonization task built upon musical memory (i.e., the subject's ability to remember the song, usually expressed by her/his ability to sing it) and rhythmic, regular movements during the exploratory phase. Musical memory is an important guide because it provides users with handy, basic information to direct movement. Moreover, in all the tests, we observed that users who exhibited a controlled exploratory phase with slow, rhythmic movements were more likely to complete successfully the melody harmonization task.

DISCUSSION

Harmonic Rhythm Interaction

Harmonic Walk is based on a physical floor interface. As the name suggests, the user interacts with the harmonic regions and chords of an instrumental piece or song through her/his steps, which must be regarded as the only human–computer interaction modality in the Harmonic Walk environment. Kinematic patterns of the gait of an adult human male (Pietraszewski, Winiarski, & Jaroszczuk, 2012) report a stride cycle time (two steps) ranging from a minimum of 0.93 s for high speed gait to a maximum of 1.26 s for low speed gait, with a preferred stride time of about 1 s. These stride times correspond to a musical speed of 60 bpm (beats per minute) for two steps and to a speed of 120 bpm for the single step. Thus, these measurements could be considered the optimal step–beat speed interaction. In the interaction with the harmonic rhythm, the user is not worried about where to move, as s/he has in front of her/him a row of tagged positions, but rather when to move. What triggers the user's step onward is the prediction of the upcoming end of the present harmonic region. But one of the difficulties of synchronizing the human step with the harmonic rhythm may be that this rhythm usually is much slower than the average stride speed. Imagining the period in Figure 3 as part of a song played at 100 bpm in a binary musical meter (two beats per bar), the harmonic region durations will be 1.2 s and 2.4 s, longer than the preferred average stride and, for the longest durations, even longer the lowest stride limit (1.26 s).

However, the embodied knowledge deriving from such step–harmonic rhythm coordination is a convincing experience of what harmonic rhythm is. Many studies have been done about the relationship between gestures and musical meaning, as documented for instance in Godøy & Leman (2010). From these studies and from personal observation, we derive the idea that the guitarist's left-hand movements on the fretboard have exactly the same entrainment rhythm we are investigating in our research because the chord changes depend on this movement. We have noticed that when singing with guitar accompaniment, musicians commonly mark the points of harmonic change by head and body movements; the same points correspond to marked accents in the right hand's strings percussion. This is a strong perceptual marker that has been observed to improve performance participation and enjoyment when playing music in a group. Also noticeable is that playing guitar involves the coordination between the left hand (harmonic rhythm) and the right hand (beat-based rhythmic pattern) and that this entrainment action links the lower level of rhythmic pattern organization to the higher rhythmic level of harmonic structure. This two-level rhythmic performance also could help in the situation—very frequent in popular music—when the change of the harmonic rhythm does not correspond to the phrases and

semiphrases organization, as shown in Figure 3, where the asterisk points out the two overlapping musical structures. The phrase change invites the Harmonic Walk user to mark it with a step, while the harmonic rhythm would require no change at all. Nevertheless, it was important to prepare the Harmonic Walk users to perform the harmonic changes through step interaction and to train them to move on the floor to accomplish the melody harmonization task. Using a simple gesture to mark the harmonic changes would not take into account that the harmonic changes must be triggered by occupying different interactive landmarks with precise spatial relationships, and that these landmarks must be reached through steps inside the circular chord mask.

Exploring the Harmonic Space

The knowledge of the harmonic space is a fundamental prerequisite for melody harmonization. What we asked from the user of Harmonic Walk is not theoretical knowledge but rather an embodied, tacit knowledge that could link her/his previously acquired harmonic experience with the chords s/he heard when occupying one of the six zones of the ring mask of the application. Thus, we posit that the user employs her/his perceptual skills to build a cognitive map of the tonality harmonic space by freely exploring the six chord zones. The freedom in this exploratory phase refers to the lack of external rhythmic constraint deriving from the audio feedback from the system.

The notable part of the exploratory movement analysis was that motion schemas are driven only by the user's perception while moving in the environment. The path s/he drew during the exploration was like a journal of how her/his brain was working to build the cognitive map of the harmonic space and, consequently, many exploratory strategies may be found. One of these strategies is the experience of recursive harmonic progressions (see Figure 5 for some examples). The progressions can be of various lengths. Nonetheless, recursive harmonic progressions return always on the tonic chord, and this repetition—together with an iterative harmonic rhythm—makes it a kind of firm ground upon which to build melodic variations and refrains.¹⁶ The trajectories of the four harmonic progressions are depicted in Figure 11, which shows how they are all concentrated around the V and I degrees. This concentration is the expression of the dominant (V degree) and tonic (I degree) hierarchical role in the tonal harmony. These harmonic progressions reflect good movement patterns because repetition reinforces the perception of harmonic functions and the learning of the spatial relationships among the various chords. Moreover, they require that the path segments among the various chords positions are repeatedly covered and with regularity. Because these progressions are simplified patterns of more extended harmonic progressions, the embodied knowledge deriving from this practice is a very useful background for melody harmonization.

Melody Harmonization

To perform a good song harmonization with the Harmonic Walk system, the user not only needs to have a clear idea of when to move, but also where to go, just as a dancer following a previously arranged choreography. The information of where to go is embedded within the cognitive map the user builds during the exploratory phase, when s/he has to link the chord sounds with the chord locations. Nevertheless, to succeed in this task implies other important abilities as well, such as musical and spatial skills, path memory, physical awareness of beat, body

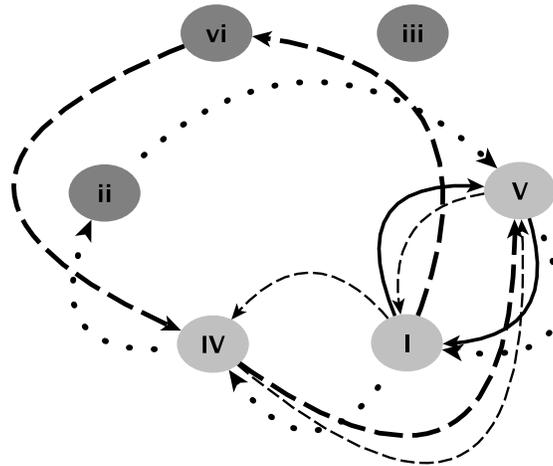


Figure 11. A spatial representation of four harmonic progressions on the Harmonic Walk interface: I-V-I (solid line), I-IV.V-I (thin dashed line), I-vi-IV-V-I (bold dashed line) and I-IV-ii-V-I (dotted line). Their trajectories show the concentration of movement around the V and I degree.

movements control, confidence, gait fluency, and the capacity for getting engaged. Moreover, the best results were observed in the nonformal experimental contexts where Harmonic Walk was used during music lessons. Here the melody harmonization was the outcome of a collaborative work, that is, when a group sang the song and members of the group took turns in trying to harmonize it by jumping from one position to the other. Cooperation offers the advantage of sharing a user's cognitive load of remembering and singing the song. Moreover, singing together with the group engages the user in the time constraints of the group's singing. This helps the user in her/his effort in achieving the task and rewards her/him in case of melody harmonization completion.

CONCLUSIONS

This paper presents a framework for the design and assessment of motion-based music applications, reviewing previous studies conducted in various fields, such as cognitive sciences and human-computer interaction. The framework has been applied to Harmonic Walk, a motion-based music application that uses an interactive space as its interface.

Harmonic Walk Future Improvements

The discussion presented above highlights some difficulties and unsolicited user reactions. Further, it offers suggestions for application design improvement and more useful utilization practices, some of which are presented here.

In designing entrainment into the harmonic rhythm regions, we used a type of forced entrainment strategy consisting of an abrupt interruption within the audio file when a certain harmonic region ended. Conceivably, a fade-out transition could have helped make the interruption less sharp but, on the other hand, a smoother interruption also might have made the

change of harmonic region less clear to the user. Nevertheless, the idea of processing the audio file to help the user predict the end of the harmonic region can be a good way to send the user a warning and to foster her/his listening attention. Various processing techniques could be employed, such as slowing down the playback speed, cross-fading the audio fragments, or using three-dimensional spatialized audio techniques.

We also discussed above that differences between the optimal stride rates and the average lengths of the harmonic regions could make the step synchronization unnatural and perhaps sometimes even clumsy. The problem could be solved by allowing the user to synchronize her/his steps at a quicker pace (i.e., with the song's beat), marking the harmonic changes with a direction shift, with a path change, or with some other spatial arrangement. Any solution in this vein may lead to interesting choreographies that can enrich the embodied meaning of harmonic rhythm changes. Moreover, because this is a case of multilevel entrainment, other technical possibilities, such as multiuser tracking or gestural tracking, also could help.

The use of Harmonic Walk in music courses or edutainment installations should be considered a "musicking" activity (Rischar, 2003), that is, an activity where every involved person has a creative function, regardless the role s/he plays. Thus, if only one user is tracked by the system, the rest of the group may help her/him in many ways. In nonresearch applications, the entire activity requires the participation of a teacher or leader who must be able to identify the group tasks and to coordinate them. Some useful tasks could involve

- (a) beating hands or percussion instrument to the pulse of the song,
- (b) singing the song,
- (c) marking the harmonic changes with hand claps or foot stumps,
- (d) making suggestions to the user regarding where to move and when to move during the song harmonization,
- (e) imitating the movements of the user during the song harmonization, or
- (f) waving in the direction of the required chord.

Following the musicking principles, much music educational technology-enhanced work can be completed in an enjoyable way. For example, crowds of young people engage in public collaborative musical rhythm entrainment activities when dancing together in discos. This kind of shared scenario could be exploited also in educational activities.

Additionally, many harmonic learning systems employ dynamic visualization to help the user link musical chords one after the other (Johnson, Manaris, & Vassilandonakis, 2014). Flashing lights or flickering arrows could indicate to the user the position of the next chord or the direction to move. Whereas such visual tags could surely be a great help for the user, this way of accomplishing the task could become a somehow mechanical activity, requiring no cognitive effort at all. It is clear that a tradeoff must be found between leaving the user alone in front of the harmonization task and suggesting the right solution to her/him. One possible solution would be to offer the user not only a unique chord solution, but also a number of alternatives based on a probabilistic base. Employing some visual projections onto the floor and/or flashing at a rate synchronized with the song's pulse could also help time coordination.

Finally, we noted above how rhythmic, regular, and slow movements during the exploration phase helped the users complete the melody harmonization task. However, it also may be useful to experiment with meaningful chord progressions, such as linking primary chords with their parallels or practicing the occurrence of harmonic progressions. To further the user's exploration,

the system could play the role of a tutor, constraining the exploration speed, and suggesting the various possible chord progressions.

Harmonic Walk Further Development

The Harmonic Walk has been tested in various contexts and discussed by users at various levels (i.e., researchers, musicians, high school and elementary teachers). What follows is a summarized excerpt of ideas collected from these subjects for Harmonic Walk's further development

At the current time, Harmonic Walk is grounded in very precise and limited harmonic rules that significantly influence the application's design and the user's interaction. The potential of employing the application with other types of music is an engaging consideration, one which could stress important commonalities among various musical genres. In particular, it is relevant to verify whether the design of Harmonic Walk can be applied in every domain with predictable and repeated patterns, similar to linguistic grammar. For instance, Harmonic Walk is based on a six-chord harmonic space (the ring), derived from the *tonnetz*, and adapted in the physical space. Although this representation is coherent with the relationships existing among the chords, its use was not found immediately clear to the users. Thus, a discussion and further investigation is necessary to understand if and how abstract concepts can be represented and acted in the physical space.

IMPLICATIONS FOR RESEARCH OR APPLICATION

The theoretical framework presented in this paper identifies three key points for the design of motion-based music applications: (a) the spatial positioning of interactive landmarks that expresses the meaning of a concept through spatial representations; (b) the user's decision on where to move, related to the user's spatial knowledge about the represented concepts; and (c) the user's decision on when to move, which depends on the user's ability to coordinate her/his motion to the timing of the selected musical event. This approach derives from the interpretation of the spatial and temporal relationships typical of the musical grammar, and thus it can lead to the development of a new type of music applications, characterized by a strong learning power and body involvement. Harmonic Walk offers a novel, creative approach to music understanding, as it allows people to experience the basic concepts of music composition that until now have been accessible only to professionals or skilled amateurs. This is made possible via the physical approach allowed by the Harmonic Walk environment. The harmonic rhythm is embodied in the time-constrained step, whereas the direction of the movements follows the position of the perceived harmonic changes. In a sense, the user play-acts the composition itself, linking her/his musical knowledge to her/his movements. This fully resonates with the pedagogical tradition of music education, which emphasizes the importance of practical experience before theoretical learning (Orff & Keetman, 1977). However, spatial representations with responsive floors and full-body interaction offer a much wider range of possibilities in that they can link the strength of embodied knowledge to the practice of abstract concepts through technology.

Moreover, the above described framework can be considered an overall strategy to model other human-computer interaction applications where spatial relationships and coordinated movement play a fundamental role, such as computer games. The movement

patterns resulting from bodily interaction in these environments are the true expression of the cognitive content conveyed by the application.

ENDNOTES

1. An interactive three-dimensional space produced by a full-body sensor like Kinect, is a user-centered space with the sensor tracking the user's torso and limbs joints; a little sensor like Leap Motion creates a sensor-centered space where the space formed by an inverted pyramid with the vertex corresponding to the sensor's position.
2. Zone Tracker is a video application that tracks the user's position. The video-analysis algorithm analyzes the input images in three steps. First the background is subtracted. Then the resulting black and white images are processed to obtain a well-shaped blob representing the user's silhouette as seen from above. Finally the blob's moves are tracked and its two-dimensional barycenter is calculated.
3. A *fermata* is a sustained note, chord, or rest whose duration is longer than the indicated value.
4. In tonal harmony, each key is represented by three fundamental harmonies: the I degree or tonic, the V degree or dominant, and the IV degree or subdominant. These harmonies are called fundamental because they summarize all the tonality's harmonic functions.
5. In the Gregorian chant notation, melodic cues are represented by neumes that are groups of notes tied together to indicate their reciprocal relationships and expressive meaning.
6. The Quadrille is a traditional dance, also called *contraddanza* or a country dance, popularized in the 19th century United States of America. It is characterized by a very precise geometrical disposition of the dancers in a double row or a square.
7. Cheraw dance (Mizoram, India) and Tinikling (the Philippines) are folkloristic dances characterized by the use of bamboo poles that are beaten on the ground and moved one against the other by two people in a rhythmic way. The dancers jump inside and outside the space between the poles in a highly coordinated way to avoid their feet clashing with the bamboo.
8. In a Schenkerian analysis, the *ursatz* (fundamental structure) corresponds to the deepest level of a tonal composition and to its most abstract form. The model is grounded on the harmonic linking of Tonic-Dominant-Tonic, with an arpeggiated bass line and a three-note step melody (fundamental line).
9. A video with an example of a collaborative song's harmonization by a 9-year-old boy with his class group is available at <https://youtu.be/c4ru468eqM0>
10. Mapping Tonal Harmony Pro information is available at <http://mdecks.com/mapharmony.html>
11. The term "responsive floor" indicates an area where it is possible to track the presence and movement of one or more users. Typically this can be done employing essentially two techniques: The first uses a system of sensorized tiles; the second is created through computer vision algorithms. By analogy, in this second case, the term responsive floor is used also if there are no sensors under the floor.
12. Dance Dance Revolution is a popular video game involving music and movement. In this consumer program, the user, moving on a sensorized platform, has to follow arrows that indicate the direction where s/he has to step. The movements are connected to various musical content.
13. Max/MSP is a visual programming language for audio and video production, algorithmic composition and signal processing written by Miller Puckette in 1980. Information is available at <https://cycling74.com/>
14. References about the Italian singer Adriano Celentano can be found at <http://ilmondodiadriano.it/>
15. A video demonstrating the harmonic space exploration by a 9-year-old boy is available at <https://youtu.be/iQIYP5dztDY>. This video effectively documents the harmonic space exploration in that the test used for high school students repeated the experimental phase with elementary school students.

16. *Refrain* is a term used both in literature and in music. It defines a repeated musical phrase, like a ritornello, and can be found in various musical styles and forms (e.g., popular songs, chorus, jazz, ancient vocal music).

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Authors' Note

All correspondence should be addressed to
Marcella Mandanici
Department of Information Engineering
University of Padova
Via Giovanni Gradenigo, 6
35131 Padova (Italy)
mandanici@dei.unipd.it

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